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Haptically Induced Illusory Self-motion and the Influence of Context of Motion

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Abstract. The ability of haptic stimuli to augment visually and auditorily induced self-motion illusions has in part been investigated. However, haptically induced illusory self-motion in environments deprived of explicit motion cues remain unexplored. In this paper we present an experiment performed with the intention of investigating how different virtual environments – contexts of motion – influences self-motion illusions induced through haptic stimulation of the feet. A concurrent goal was to determine whether horizontal self-motion illusions can be induced through stimulation of the supporting areas of the feet. The experiment was based on the a within-subjects design and included four conditions, each representing one context of motion: an elevator, a train compartment, a bathroom, and a completely dark environment. The audiohaptic stimuli was identical across all conditions. The participants' sensation of movement was assessed by means of existing measures of illusory self-motion, namely, reported self-motion illusion per stimulus type, illusion compellingness, intensity and onset time. Finally the participants were also asked to estimate the experienced direction of movement. While the data obtained from all measures did not yield significant differences, the experiment did provide interesting indications. If motion is simulated through implicit motion cues, then the perceived context does influence the magnitude of displacement and the direction of movement of self-motion illusions as well as whether the illusion is experienced in the first place. Finally, the experiment confirmed that haptically induced illusory self-motion in the horizontal plane is indeed possible.

1 Introduction

During our everyday interaction with the world the sensation of self-motion remains largely unnoticed. However, we become increasingly concious of this sensation during those rare moments where we experience a sensation of movement despite being stationary. A well-known example is the incorrect motion perception one may experience when being on a motionless train, looking out the window at the adjacent track where another stationary train is located. When this second train departs from the station, one may experience a transient, yet compelling, illusion of being on the train which is moving. This experience is a naturally occurring instance of visually induced illusory self-motion, also referred to as vection [6]. Our susceptibility to such illusions may at least in part be explained by the misleading nature of visual motion stimuli [3]. That is to say, visual motion stimuli are open to not one, but two perceptual interpretations [1].

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Either the sight of the moving train leads to to egocentric motion perception if the train passenger correctly perceives himself as being stationary while the train in the adjacent track is moving, or else the visual stimuli lead to exocentric motion perception if the train passenger falsely perceives the surroundings as being stationary while he is moving. Self-motion illusions occurring along some line are refereed to as linear illusory self-motion, while the erroneous sensation of rotation about one or more of the three bodily axes is refereed to as circular illusory self-motion [16].

Self-motion illusions are influenced by the properties of the physical stimuli (bottom-up factors) as well the perceiver's expectations to, and interpretation of, the stimuli (top-down factors) [13]. Riecke and colleagues [11] summarize a number of the bottom-up factors that may influence the onset time, duration, and intensity of the self-motion illusion. These factors include, but are not limited to, the movement speed of the stimulus, the area of the visual field occupied by the display, and the perceived depth structure of the visual stimulus. While the influence influence of bottom-up factors have been studied extensively (e.g.[2,4,18]), evidence suggesting that top-down factors are consequential does exist. To exemplify, it has been shown [13,9,19] that both circular and linear self-motion illusions may be influenced by whether participants are seated in a chair that potentially could move as opposed to one that is immovable. Moreover, it has been been demonstrated that self-motion illusions in some circumstances may be influenced by whether the participants,before being exposed to visual motion stimuli, are asked to attend to the sensation of self-motion or object motion [8]. Auditory motion stimuli is, just as their visual counterparts, open to not one, but two perceptual interpretations, and they may thus lead to either exocentric or egocentric motion perception. Indeed, a sensation of self-motion may be experienced by blinded listeners exposed to sound sources moving relative to their position [16].

In this paper we describe an experiment performed with the intention of investigating how different contexts of motion influence haptically induced illusory self-motion on behalf of individuals exposed to virtual environments devoid of any explicit motion cues. To be more exact, we compared four scenarios involving identical implicit motion cues (auditory and haptic stimuli), but different contexts of motion (visual stimuli depicting an elevator, a train, a bathroom, and a completely dark environment).

2 Related Work

Research on haptically induced illusory self-motion is rather scarce and with a few exceptions [14,7] the experiments have generally focused on whether this form of stimuli positively influences an illusion of movement facilitated by stimulation of another modality [12,17].

Väljamäe and colleagues [17] describe a study performed with the aim of investigating whether sensation of auditorily induced linear illusory self-motion may be intensified by the addition of vibrotactile feedback delivered by means of low frequency sound and mechanical shakers. The authors of that study found that the self-motion illusion was significantly higher during exposure to the mechanically induced vibration. Notably their results also showed that the auditory-tactile simulation of a vehicle engine was as effective as illusions induced via auditory feedback including explicit motion cues, i.e., moving sound fields. Riecke et al. [12] similarly describe an experiment investigating whether physical vibrations of the perceivers' seat and footrest enhance visually induced circular vection. They found that the addition of this form of vibrotactile feedback entailed a slight, yet significant, enhancement of the self-motion illusion.

As it is the case for the influence of haptic feedback on illusory self-motion, also vertical self-motion illusions, that is, perceived movement along the longitudinal axis, remains almost unexplored. One such study, performed by Wright and colleagues [19], aimed at investigating the vestibular and visual contributions to vertical illusory self-motion.

Inspired by the study described by Roll et al. [14], Nordhahl and colleagues [7] performed an experiment intended to determine if it is possible to facilitate vertical illusory self-motion on behalf of unrestrained participants exposed to a immersive VE by haptically stimulating the main supporting areas of their. The dominance of vertical self-motion illusions in the experiment described by Nordahl et al. [7] is arguably a testament to the influence of top-down factors. The participants' past experiences entailed that the context of motion (the virtual elevator) may have coloured their interpretation of the implicit motion cues delivered through auditory and haptic feedback. We hypothesize that when no explicit motion cues are present, then the context of motion may fluencine self-motion illusions induced through implicit motion cues. That is to say, 1) Self-motion illusions are more likely to occur during exposure to virtual environments where the context of motion suggests that movement indeed is possible. 2) The experienced magnitude of displacement is likely to correspond to the magnitudes of displacement associated with the particular context of movement. 3) If the context of motion suggests that movement in a particular direction is possible, then illusory self-motion in that directions is more likely to be experienced.

The experiment described in the current paper should to a large extent be considered as a continuation of work described by Nordahl et al. [7] since it was performed with the intention addressing these three claims. Moreover this implies that it was an implicit goal to determine whether it is possible to induce horizontal self-motion illusions within the context of a virtual environment by haptically stimulating the feet of unrestrained participants.

3 Experiment Design

A within-subjects design was used in order to minimize the effects of the high between-subject variability which often is found in studies of illusory self-motion [10]. The experiment included four conditions, each one representing a different contexts of motion. The virtual environments used to represent the four contexts of motion were the interior of an elevator, a train carriage, a bathroom, and a completely dark environment. The elevator and the train were chosen because they sere as contexts suggesting linear, vertical and horizontal movement, respectively. The particular bathroom was chosen on grounds that it was regarded as unlikely that individuals associate this room with movement. Finally the dark environment was included since it did not impose a context of motion upon the participants. While the visual stimuli differed across the four conditions, the auditory and haptic stimuli were identical. The auditory feedback comprised sounds reminiscent of those produced by an engine. However, these were not identifiable as any particular vehicle or machine. The signal used to control the haptic feedback was a sawtooth waveform. This signal was chosen based on the findings of Nordahl et al. [7]. The intention was for the auditory and haptic stimuli to serve as implicit motion cues. All the stimuli used for the experiment were were devoid of any explicit motion cues. The elevator had opaque walls, the windows of both the train and the bathroom were covered by blinds, and the dark environment did not include visual feedback of any kind. The sound was similarly not spatialized.

3.1 Environment Simulation

The four virtual environments were simulated using the same multimodal architecture used by Nordahl et al. [7]. This architecture was originally developed for the purpose of simulating walking-based interactions through visual, auditory and haptic stimuli [15].

Simulation Hardware. The user interacts with the system by performing natural movements which in turn are registered by the system. The position and orientation of the users head is tracked by means of a 16 cameras Optitrack motion capture system (Naturalpoint) and the forces exerted during foot-floor interactions are registered by a pair of customized sandals augmented with actuators and pressure sensors [15]. Two FSR pressure sensors (I.E.E. SS-U-N-S-00039) are placed inside the sole of each sandal at the points where the toes and heel come into contact with the sole. The analogue values of each of these sensors were digitalized by means of an Arduino Diecimila board. The actuators responsible for delivering the haptic feedback are placed at roughly the same positions. Each sandal is embedded with four of these electromagnetic recoil-type actuators (Haptuator, Tactile Labs Inc., Deux-Montagnes, Qc, Canada), which have an operational, linear bandwidth of 50 to 500 Hz and can provide up to 3 G of acceleration when connected to light loads. Figure 1 illustrates the placement of the pressure sensor and actuators in the heel of one sandal. The visual feedback is delivered through a nVisor SX head-mounted display, with a resolution of 1280x1024 in each eye and a diagonal field of view of 60 degrees. While the multimodal architecture in its original form is capable of delivering auditory feedback using a surround sound system composed by 12 Dynaudio BM5A speakers, a set of headphones (Ultrasone HFI-650) were used during the current experiment. The reason being, that the actuators generate sound while activated, which might make up an undesirable bias. Thus the headphones both served the purpose of providing auditory feedback and masking out the undesired sounds.

Simulation Software. The visual representations of the four environments (see Figure 2) were produced in the multiplatform development environment Unity 3d which facilitates stereoscopic viewing by the placement of two cameras within one environment. Dynamic eye convergence and divergence was simulated by means of a simple raycasting algorithm ensuring that the cameras are always aimed at the closest object immediately in front of the user. The auditory feedback was based on a recording of an industrial fan (freesound.org). The recording was edited into a loop which is 7.3 seconds long and loops seamlessly. The audio loop was played back at 30% reduced speed. A

Fig. 1. Placement of a pressure sensor and two actuators in the heel of one sandal

high-pass and a low-pass filter was added to allow for fine tuning of the playback during the final preparations of the experiment. The auditory feedback was delivered using the Max/MSP realtime synthesis engine, which also was used for the synthesis and delivery of the signal used to control the actuators providing haptic feedback. The signal in question was a sawtooth waveform with a frequency of 50 Hz and a symmetric trapezoidal envelope. This signal was chosen since it was the one that Nordahl et al. found the most effective at eliciting self-motion illusions [7]. The data obtained from the pressure sensors was used to ensure that vibration only was activated when the foot is in contact with the ground. A schematic drawing the multimodal architecture used to simulate the virtual elevator can be seen on Figure 3.

3.2 Measures of Illusory Self-motion

The participants' experience of illusory self-motion was assessed by means of existing measures of self-motion illusions, namely, reported self-motion illusion per stimulus type, illusion compellingness, intensity and onset time [16].

The reported self-motion illusion per stimulus type simply corresponds to a binary measure of whether illlusory sef-motion were experienced or not. The compellingness (or convincingness) of the illusion was assessed by asking the participants to rate their sensation on a magnitude estimation scale from '0' to '5' where '0' signified no perceived movement and '5' corresponded to fully convincing movement.

The intensity of the illusion was measured by asking the participants to estimate the magnitude of the displacement on a scale familiar to them (meters or feet). No experienced movement would correspond to a displacement of zero meters. It should be noted that past experiments where intensity has been operationalized as the magnitude of the displacement [19], have included stimuli providing information about the distance to, or size of, objects based on which estimates of distance could be made. The illusion onset time (or latency) was measured as the time elapsed from the onset of the stimuli until the onset of the illusion. The measures of both compellingness, and intensity were adapted from [19]. Finally the participants were asked to estimate the direction in which the believed to have moved.

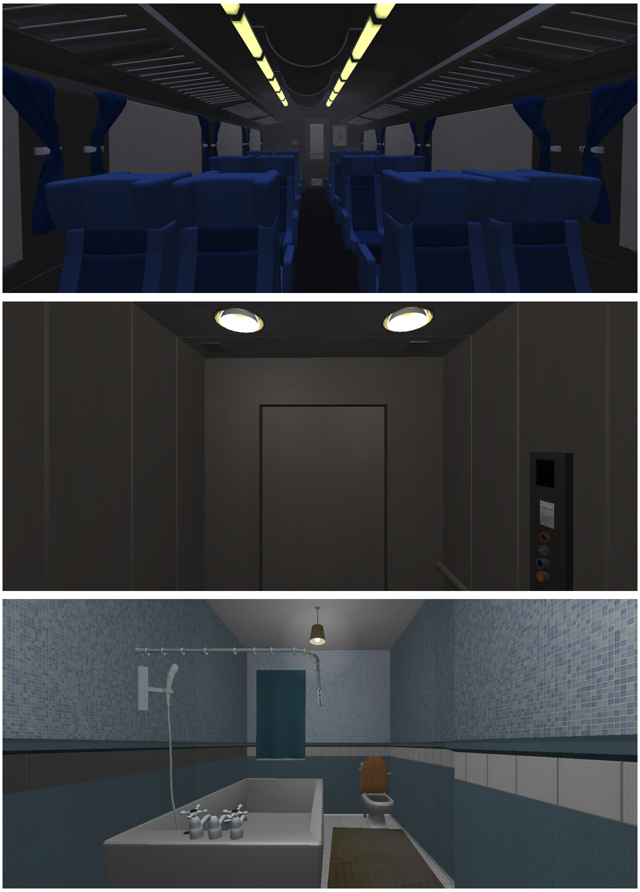

Fig. 2. Screen shots of three of environments used for the experiment: the train, the elevator, and the bathroom

3.3 Participants and Procedure

A total of 18 participants partook in the experiment (15 men and 3 women) aged between 19 and 40 years (mean = 25.8, standard deviation = 5.4). Before exposure to the VE, the participants were introduced to the scenarios they were about to experience and were asked to attend to the sensation of movement. Moreover it was stressed that we were interested in the participants' honest opinion rather than answers brought about by any assumptions regarding the demand characteristics of the experiment. During the exposure to the four virtual environments the participants were placed on a wooden platform, which they were made to believe might move during one or more of the conditions. The participants were unable to see the experimental setup for the duration of the experiment. This was done since it has been shown that the convincingness of self-motion illusions significantly increases when subjects believe that actual motion may occur [13]. Before the beginning of each trial the participants were placed at the same

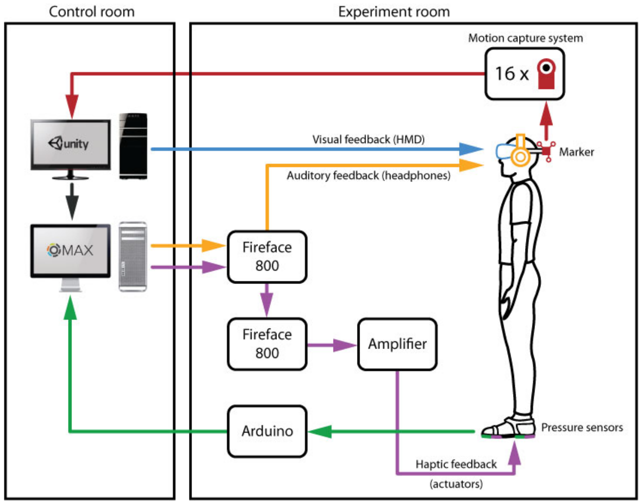

Fig. 3. A schematic drawing of the multimodal architecture used to simulate the virtual environments

position and were asked to face the same direction. The participants were exposed to all four conditions for one minute and after each exposure the participants were asked to answer the provided questions verbally. The order of the conditions was randomized so as to control potential order effects.

4 Results

Table 1 shows the results pertaining to the reported self-motion illusion per stimulus type, that is, the number of participants who experienced a self-motion illusion across the four conditions. However a comparison by means of a Cochran's Q test did not yield any significant difference between the four conditions ($Q(3) = 6.0567, p = 0.11$).

Table 2 summarizes the results obtained from the measures of illusion onset time, compellingness, and intensity. The bar charts presented in figures 6 and 5 provide a graphical overview of these three sets of results. One-ways analyses of variance (ANOVAs) were used to compare the averages obtained from the measures of the compellingness and intensity of the self-motion illusion across the four conditions Significant differences was found in relation to illusion intensity ($F(3,41) = 5.28, p = 0.003$). While the analysis of the results pertaining to illusion compellingness was borderline significant ($F(3,68) = 2.38, p = 0.07$) the same cannot be said of the results related to

Table 1. Reported self-motion illusion per stimulus type

Elevator	Train	Bathroom	Dark
13	15	8	11

Table 2. Mean ± one standard deviation pertaining to three of the measures of illusory self-motion. Values in parenthesis indicate the number of reports based on which the mean and standard deviations were determined.

	Compellingness	Intensity (meters)	Onset time (sec.)
Elevator	2.3 ± 1.8 (18)	27.8 ± 33.8 (14)	19.9 ± 13.57 (10)
Train	2.7 ± 1.7 (18)	443.5 ± 623.1 (10)	22.8 ± 17.9 (14)
Bathroom	1.2 ± 1.5 (18)	25.0 ± 62.2(12)	22.7 ± 9.3 (5)
Dark	1.9 ± 1.9 (18)	12.8 ± 33.1 (9)	26.1 ± 13.4(8)

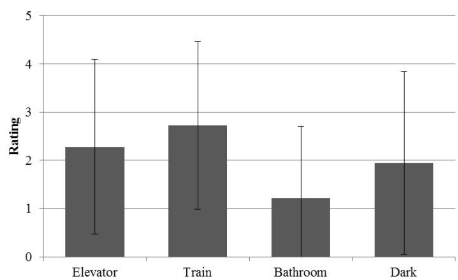

Fig. 4. Mean compellingness ratings. Error bars indicate ± one standard deviation.

the illusion onset time ($F(3,33) = 0.25, p = 0.86$). The latter did not come as a surprise since the number of registered onset times differed greatly from condition to condition, since a large number of participants neglected to report the onset time and no times recorded when no illusion was experienced. Subsequently post-hoc analysis of the results pertaining to illusion intensity was performed by means of Tukey's procedure. This pairwise comparison of the means revealed that conditions the Train condition differed significantly from the remaining three while none of the three differed significantly from one another.

Finally, Table 3 summarizes the results pertaining to the question of what direction the elevator was moving in. It is worth mentioning that three participants experienced movement in directions which differed from the norm. When exposed to the virtual

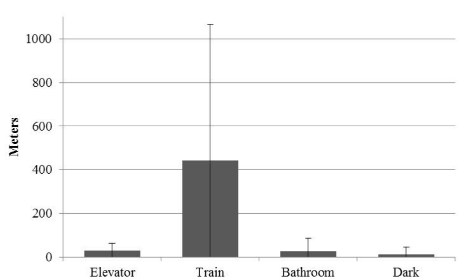

Fig. 5. Mean illusion intensity in meters. Error bars indicate ± one standard deviation.

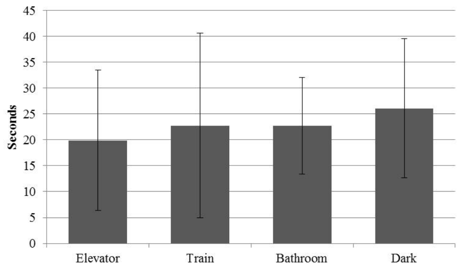

Fig. 6. Mean illusion onset time in seconds. Error bars indicate ± one standard deviation.

Table 3. Frequency of the participants' estimates of the direction of movement across the four conditions. The directions are relative to the participants' orientations at the beginning of each trial, which were identical for all participants.

	Elevator	Train	Bathroom	Dark
Upwards	7	0	0	2
Downwards	6	0	0	3
Forwards	0	9	5	1
Backwards	0	3	0	1
Other	0	0	2	1
Unsure	0	3	1	3

bathroom one participant experienced leftwards movement, while another experienced illusory full-body leaning, alternating from one direction to another. Finally, one participant experienced ”roller-coaster like movement” when exposed to the dark condition, that is, the participant had a sensation of moving forward while simultaneously either moving up or downwards.

5 Discussion

Interestingly the reported self-motion illusion per stimulus suggests that all four contexts of motion may elicit self-motion illusions. Indeed more participants experienced illusory self-motion when exposed to the train, compared to the elevator. Thus it would seem that haptically induced illusory self-motion is possible. While no significant differences between the four groups were found, it is notable that the bathroom elicited the lowest number of illusions on behalf of the participants. This indication is to some extent also mirrored in the results obtained from the employed measure of illusion compellingness. That is, exposure to the bathroom gave rise to the least compelling illusions of movement. Previously we suggested that self-motion illusions may be more likely to occur during exposure to virtual environments where the context of motion suggests that movement indeed is possible. At first glance, the obtained results seems to contradict this claim. The context of motion suggesting no movement (the bathroom) did yield self-motion illusions on behalf of some participants. However five of the eight participants who experienced illusions in this environment remarked that they had become convinced that they were on a ship. Considering that the bathroom was purposely selected because it did not appear like a bathroom one would find on a normal ship, plane or other moving vehicle, it is interesting that close to a third of the participants made up exactly this explanation when attempting to make the seemingly conflicting information meaningful. With some caution, one may argue that this indicates just how far our brains are will to go in order to integrate conflicting multimodal stimuli into one meaningful percept. So it would seem that some of the participants after all did rely on the top-down factors since the illusion may have been made possible by their expectations to, and interpretation of, the stimuli.

A significant difference was found between the mean illusion intensity related to the train condition and the remaining three conditions. However, this does not necessarily imply that the self-motion illusions experienced during exposure to the train are superior to the ones elicited by the elevator or the other two conditions for that matter. It suggests that the audiohaptic stimuli in average leads to an experience of a larger displacement when paired with virtual train. This does arguably lend some credence to the claim that the experienced magnitude of displacement is likely to correspond to the magnitudes of displacement associated with the particular context of movement. It is interesting to note the large standard deviation pertaining to this mean. However, it seems possible that the disagreement amongst the participants may be explained by the large range of possible speeds achievable when on one is a train.

The vast majority of the participants who experienced illusory self-motion during exposure to the elevator and the train did so in the vertical and horizontal plane, respectively. The few who did not follow this pattern were did not experience illusions were not meaningful given the supplied context of movement, but were unsure about the direction of movement. Notably the results seemed to correspond with the ones reported by Nordahl et al. [7] since no tendencies seem readily apparent in regards to the perceived direction of movement elicited by the virtual elevator. That is to say, while they all experienced vertical movement, an almost equal number experienced forwards and backwards movement. The same is not true in regards to the train. When exposed to this virtual environment most of the participants experienced forward movement. Anecdotal evidence obtained from one participant may provide a possible answer. This participant explained that the cable connected to the head-mounted display had caused him to experience forward movement. The subtle resistance provided by the cable may in some capacity have been experienced as the gravitational force experienced during acceleration and since this cable was connected behind the participants during the beginning of each trial this may have lead to the interpretation of the train moving in that particular direction. Moreover it is interesting to not that most of the participants who experienced movement inside the virtual bathroom did so in the horizontal plane. The directions of movement experienced during exposure to the dark environment were less consistent. It would seem that this data is in support of the claim that if the context of motion suggests that movement in a particular direction is possible, then illusory self-motion in that directions is more likely to be experienced. This is particularly evident from the results related to the virtual elevator and train. However, it is interesting to note that the bathroom condition, which were interpreted as a the interior of a ship, primarily left to illusions in the horizontal plane while the dark environment, which were open to more interpretations, also lead to less consistent answers.

6 Conclusion

In this paper we have described an experiment performed with the intention of investigating how different contexts of motion influences self-motion illusions induced through haptic stimulation of the feet. The experiment was based on the a within-subjects design and all 18 participants thus experienced the same four conditions. The audiohaptic stimuli was identical across all conditions but the context of motion was varied. The participants experienced the interior of an elevator, a train compartment, a bathroom, and a completely dark environment. The four virtual environments were devoid of any explicit motion cues and the resulting self-motion illusions were thus the consequence of implicit motion cues. The participants' sensation of movement was assessed by means of self-reported measures of illusory self-motion, namely, reported self-motion illusion per stimulus type, illusion compellingness, intensity and onset time. Finally the participants were also asked to estimate the experienced direction of movement. While the data obtained from all measures did not yield significant differences the experiment did provide interesting indications. It would seem that if motion is simulated through implicit motion cues, then the perceived context does influence the magnitude of displacement and the direction of movement of self-motion illusions as well as whether the illusion is experienced in the first place.

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